



**Interactive Model-Centric Systems Engineering (IMCSE)**  
**Phase 5**

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## EXECUTIVE SUMMARY

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The Interactive Model-Centric Systems Engineering (IMCSE) research program arises from the unique opportunity to investigate the various aspects of humans interacting with models and model-generated data, in the context of systems engineering practice. IMCSE research aims to develop transformative results through enabling intense human-model interaction, to rapidly conceive of systems and interact with models in order to make rapid trades to decide on what is most effective given present knowledge and future uncertainties, as well as what is practical given available resources and constraints. While model-based engineering initiatives are advancing technical aspects of models in the engineering of systems, this research advances knowledge relevant to human interaction with models and model-generated information.

Figure 1 highlights several questions the research seeks to address.

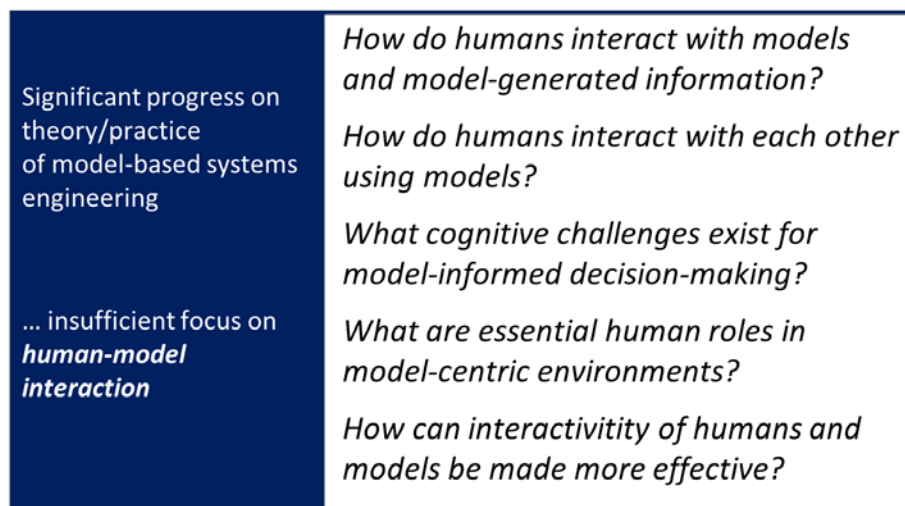


Figure 1 Areas of Inquiry

This report discusses outcomes of Phase 5 of the IMCSE research program, focusing on three areas:

**Human-Model Interaction.** The empirical study on model-centric decision making, initiated in Phase 4, was completed, and feedback was obtained in several technical exchanges with the practitioner community. The empirical study findings, analogy studies, and other secondary source data were used to develop a set of guiding heuristics. Several validation activities were conducted, towards the final goal of developing a validated set of guiding principles for effective human-model interaction. State-of-the-practice findings were used as a basis for conducting a technical exchange workshop with research stakeholders. The workshop provided research feedback and identified needs for improving the state-of-the-practice for human-model interactivity.

**Interactive Epoch-Era Analysis.** Research matured the approach for evaluating systems under dynamic uncertainty. The extended framework for interactive capability and scaling to big data was completed, including several interactive prototypes for demonstration purposes. Demonstration cases were completed for a space tug multi-mission orbital transfer vehicle and a commercial offshore ship. The framework can be applied for both modular and non-modular solutions for comparison within a tradespace (which helps to assess the lay-in, opportunity, and carrying costs of modularity), and as a means for determining the costs and benefits of having the option to switch between states (e.g. swapping a mission payload or manufacturing line). IEEA involves both visualization and interaction to varying degrees. An experiment to investigate the impacts of visualization and interaction in a decoupled manner, initiated in Phase 4, was completed, with several findings. A set of knowledge assets was completed including the Interactive EEA framework, demonstration prototypes, case-based impact studies, and results of the experiment.

**Curation of Model-Centric Environments.** Prior phase research reinforced the interest and need for organizations to perform a model curation activities. Under the premise that model-centric environments of the future will necessitate specialized leadership and competencies, a new leadership role for curation was further investigated. Four stages were identified for organizations transforming under the digital paradigm. Specific needs were identified for establishing leadership and practices for model curation through primary and secondary sources. Investigations suggest seven different types of organizations for implementing model curation, based on different needs and organization forms. Research findings were shared with research stakeholders as a preliminary validation of needs and emerging practices. The need for an instrument for organizations to assess their model leadership capabilities and risks was confirmed in a technical exchange workshop and other meetings with research stakeholders.

IMCSE research was presented and discussed with practitioners and sponsors in numerous research meetings and workshops throughout Phase 5. These included SERC events, NDIA SE Conference, INCOSE International Workshop, and various meetings at MIT and other research stakeholder locations. These interactions have provided valuable feedback and inputs to the research activities, and served to discover relevant research ongoing in the larger systems community.



## **INTERACTIVE MODEL-CENTRIC SYSTEMS ENGINEERING (IMCSE) PHASE 5 RESEARCH**

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Models are increasingly used to drive major acquisition and design decisions (Zimmerman et al., 2017), yet model developers, analysts, and decision makers are faced with many challenges. The systems community has made progress on standards, methods and techniques for model-based engineering, yet little focus has been given to complexities of human-model interaction.

Interactive Model-Centric Systems Engineering (IMCSE) research generates knowledge impacting human effectiveness in model-centric environments of the future (Rhodes & Ross, 2016). The Phase 5 research provided the opportunity to build on the research outcomes of the prior phases. This report discusses the findings of three areas of focus:

1. Human-Model Interaction
2. Interactive Epoch-Era Analysis
3. Curation of Model-Centric Environments

## HUMAN-MODEL INTERACTION

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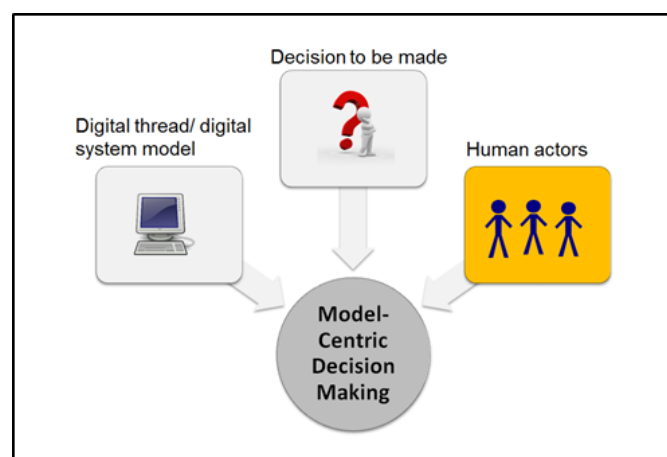
Addressing complex systems problems requires both human intelligence and the use of digital system models. Open areas of inquiry include: how individuals interact with models; how multiple stakeholders interact using models and model generated information; facets of human interaction with visualizations and large data sets; and underlying fundamentals such as model purpose and model handling.

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### BACKGROUND

The research is based on the belief that human-model interaction needs to be specifically considered, given models are an abstraction of reality and there are unique factors and considerations. A science of human-systems integration (HSI) has emerged, yet focus is on humans within operational systems, while models are abstractions of reality. The relatively mature field of human-computer interaction (HCI) offers valuable insights, however focus is on designing computer interfaces. A report of a recent workshop sponsored by the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), the Air Force Office of Scientific Research (AFOSR), and the National Modeling and Simulation Coalition (NMSC), highlights the need for understanding the individuals involved in the modeling process and how these individuals affect model development and usage (NSF, 2016).

Recent research studies have provided insight into the “state of the practice” on human-model interaction and decision making with models (Rhodes & Ross, 2016, German, 2016). As shown in Figure 2, there are three elements involved in model-centric decision making: the decision to be made, the digital thread/digital system model, and the human actors. The focus of this study is on the human actors.



**Figure 2 Elements of Model-Centric Decision Making**

One activity in this research program is investigation of guiding principles for human-model interaction. The principles are expected to result from a formal iterative evaluation, refinement and testing of the heuristics that have been identified through a variety of research activities.

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## **RESEARCH APPROACH**

Our research on human-model interaction has investigated the literature across various fields including cognitive science, decision analysis, organizational and human behavior, and systems science. Several secondary source research studies provided “analogy case” insights from situations having similarities to the transition from traditional engineering environments to model-centric engineering environments (German & Rhodes, 2016; German, 2017). Knowledge was also drawn from related fields of human-systems integration (HSI), human computer interaction (HCI), and Visual Analytics (VA), as relevant to the research (Pew & Mavor, 2007; Shneiderman et al., 2016; Thomas & Cook, 2005).

Key research themes emerged from these investigations, in addition to themes identified through a pathfinder research workshop involving expert practitioners and researchers (Rhodes & Ross, 2015). An exploratory interview-based study of model-centric decision making resulted in findings drawn from thirty subject matter experts (German & Rhodes, 2017). Candidate heuristics were derived primarily from the expert interviews, as supported by insights from the literature investigation and second source studies. A series of individual and group activities were used for preliminary validation and refinement of heuristics.

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## **IMPORTANCE OF ENDOGENOUS PERSPECTIVE**

Investigation of human-model interaction and model-centric decision making has underscored the need to view humans as endogenous constituents within model-centric engineering environments. The endogenous point of view, as asserted by Forrester, starts with the question of where is the boundary “that encompasses the smallest number of components, within which the dynamic behavior under study is generated?” (Richardson, 2011).

By drawing the boundary, models and human actors are designated as constituents within the environment. This contrasts with how humans are often viewed as being “on the loop”, interacting with the environment as an external agent. Models represent an abstraction of reality, and can come in a variety of forms and formats, but fundamentally they are an encapsulation of reality that humans use to augment their ability to make sense of the world and anticipate future outcomes. The idea that “humans use” models, highlights human interaction as a necessary factor within all models.

In the emerging model-centric practice, model and humans are intertwined. Models are used by humans and that interaction influences how models are conceived and used in decisions. Models and model-generated information influences decision maker behavior in various ways.

Together, humans and models exhibit dynamic behavior. Understanding human-model interaction is predicated on taking this endogenous point of view.

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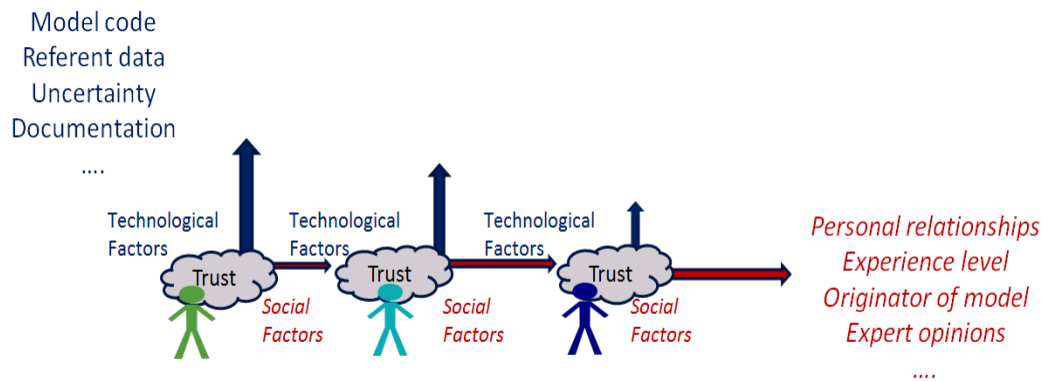
## **MODEL-CENTRIC DECISION MAKING**

Understanding the current state of the practice is an important step in model-centric enterprise transformation. The findings in our recent interview-based study involving 30 experts led to insights, along with information from literature and secondary source studies, have informed the derivation of heuristics for human-model interaction. Findings in the study include the areas below, with two of these areas briefly described. A more detailed discussion of the findings is presented in a recent paper (German & Rhodes, 2017) and in the IMCSE Phase 4 report (Rhodes & Ross, 2017).

- Three actor decision flow
- Understanding of assumptions and uncertainty
- Technological and social factors influencing trust
- Importance of documentation and model pedigree
- Using models as primary versus supplementary
- Model transparency and model trust
- Factors and biases limiting model-centric decisions
- Modes of interaction with models

## **MODELS AND TRUST**

A major theme arising from an interview-based study of current model-centric decision making showed a pattern described as a three actor decision flow (German & Rhodes, 2017). The flow begins with the modelers and ends with the ultimate decision maker. In the middle of the flow is the “through” person who is a trusted agent of the decision maker. The data suggests that as actors move further along the flow of information and have less time and ability to personally investigate a model and build their own trust in the model, their trust instead shifts more onto their people to investigate the model for them. Trust for the ultimate decision-maker is “implicitly on the models, but explicitly on the people.” A combination of technical and social factors is involved, as shown in Figure 3.



**Figure 3. Three Actor Decision Flow**

A model does not provide value by existing. Rather, it provides value by producing information that can be used by individuals and decision-makers to better understand a specific problem. Often, information flows *from* initial actors that directly interface with a model before flowing *through* other individuals within the decision-making process and ultimately *to* final decision-makers. All actors in the model-generated flow of information must have a well-calibrated understanding of the model if the information is to be effectively understood.

#### VARIOUS FACTORS LIMITING EFFECTIVE MODEL-CENTRIC DECISIONS

The model-centric decision-making study revealed factors perceived as limiting effective model-centric decisions. While technical (model-related) factors are cited, the majority of limitations that the expert interviewees raised related to human (social and cultural) factors. Figure 4 shows selected examples of factors cited in the interviews.

MODEL	HUMAN		
Data availability	Talent of people	Skill level	Generational differences
Data quality	Inertia to change	Ability to socialize models	Organizational differences
Model complexity	Communication barriers	Lack of trust/fear of the unknown	
Inadequate methods	Changing preferences of decision-makers	Lack of understanding	
Lack of transparency and model documentation	Unwillingness to share models or information	Educated leadership	
Interactivity with models	Time and money	Lack of desire to understand	
	Team agreement	Bad past experiences	

**Figure 4 Factors Limiting Effective Model-Centric Decisions**

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## HUMAN-MODEL INTERACTION HEURISTICS

The research has informed an initial body of heuristics that encapsulate strategies that can be used in practice for several purposes. Sources of information include the IMCSE Pathfinder Workshop (Rhodes & Ross, 2015), theory and secondary sources, analogy cases (German & Rhodes, 2016) and the expert-interview study (German & Rhodes, 2017).

Multiple purposes are proposed for the heuristics. These include educating novices, conducting expert forums, informing policy and practice, and conducting program team launches. Heuristics can be thought of as prescriptive theories that offer “suggestions to facilitate more extensive search for useful possibilities and evidence” (Baron, 1988). Maier & Rechtin (2000) define heuristics as “sophisticated abstractions of lessons learned from experience.” Such condensed and codified abstractions of practical experience should be thought of as tools to assist individuals in design and decision-making. There may be hundreds of potential heuristics available to a decision-maker, “but only a few are needed at any one time and for a specific job at hand” (Maier & Rechtin, 2000). Heuristics are “guides along the way,” but also “must be used with judgment”. There is an art to this discernment, not in evaluating the wisdom of heuristics themselves, but “in the wisdom of knowing which heuristics apply” to a given problem (Maier & Rechtin, 2000).

Recent research studies have shown the benefit of using heuristics to assist novice engineers in early design activities (Yilmaz et al. 2016, Murphy et al., 2017). Using heuristics for launching an engineering effort is supported by Maier & Rechtin (2000); the authors state they are “trusted, nonanalytic guidelines” and can be used “as aids in decision making, value judgements and assessments”.

The heuristics generated in this research have been initially validated through several activities, and subsequently refined. Further work is ongoing to fine-tune the heuristics, as well as expand the set based on additional research. Ten heuristics are presented and explained below.

### **HUMANS SHOULD NOT BE FORCED TO ADAPT TO MODELS, RATHER, MODELS SHOULD BE DESIGNED FOR HUMANS.**

Evolving technology enables more complex and capable models but may not increase effectiveness if humans are not appropriately considered. Humans have cognitive and perceptual limitations that limit the amount and type of information they can effectively comprehend and use to make decisions. Designing for humans requires understanding their capabilities and limitations so that the model intelligence can extend the overall system intelligence. Model designers must consider the users and how the model will influence their behavior and decisions.

**MODEL DEVELOPERS, MODEL USERS, AND ORGANIZATIONS SHARE RESPONSIBILITY FOR PREVENTING IMPROPER MODEL USAGE.**

Model developers have the responsibility to make capabilities and limitations of a model salient and understandable, to enable decisions on proper use. Model users have the responsibility to obtain and use this information in determining use/reuse of a model, as well as documenting this decision with assumptions. Organizations have the responsibility to prevent the improper use of models in general, through effective policies, practices and controls.

**MODELS DO NOT HAVE AGENCY -- THE ULTIMATE RESPONSIBILITY FOR DECISIONS MUST BE UPON HUMANS.**

Increasingly complex and automated modeling environments may make it easier to attribute agency and responsibility to models. The ultimate decision-making authorities are people and blame cannot be placed upon models for poor decisions. Individuals should be aware of the potential for improperly diffusing responsibilities for decisions upon models, and policies should clearly establish the responsibilities for which individuals are held accountable.

**BEFORE ANY MODEL CAN BE USEFUL, ITS CAPABILITIES AND LIMITATIONS MUST BE REVEALED AND UNDERSTOOD.**

All models are inherently abstractions of reality that contain assumptions about the modeled system, and these assumptions limit the applicability of where and how the model can be used. Numerous empirical examples show that poorly understood and applied models have led to programmatic challenges and failures. An improper understanding of a model's limitations may lead to decision-makers inappropriately applying it beyond its limitations. Conversely, if a model's capabilities are not fully understood, decision-makers may not use the model to its fullest potential.

**MODELS ARE CREATED FOR SPECIFIC REASONS AND CONTEXTS THAT FUNDAMENTALLY BOUND A MODEL'S APPLICABILITY.**

A model may be insightful and valuable within one problem context, but the assumptions built into the model may not be valid within some other contexts. Evaluating a model's applicability should not just consider whether it has been verified and validated, but also under what conditions and in what contexts. Using a model outside of its inherent bounds may lead to model results that are inappropriate for the problem under consideration.

**MODEL DOCUMENTATION SHOULD MAKE THE ASSUMPTIONS AND LIMITATIONS OF A MODEL EXPLICIT; OTHERWISE IT WILL NOT BE USABLE BY ANYONE OTHER THAN THE ORIGINATOR.**

Model developers carry the most intimate understanding of a model's assumptions and limitations. If decision-makers are those other than the modelers, however, assumptions and limitations must be clearly documented so that others might calibrate an appropriate personal understanding of the model. Documentation should not only capture the assumptions built within the model, but the assumptions made about the model itself. Conceptual "white board" artifacts created early in a model's development can offer insight into decisions made about a model, including what problem contexts the model is designed for. With this line of thinking,

both decisions made regarding assumptions within the model's code and the decisions made before the model was even designed should be documented. If these assumptions and limitations are not documented and accessible, users and decision-makers will not be able to appropriately calibrate their understanding and trust of the model, which makes it unusable.

**MODEL TRUST IS A SOCIOTECHNICAL CONSTRUCT. YOU MUST EXAMINE BOTH TECHNICAL AND SOCIAL FACTORS TO UNDERSTAND HOW INDIVIDUALS DEVELOP TRUST IN MODELS.**

Individuals within the model-centric decision-making process rely upon various technical and social factors to develop trust in a model. Technological factors include technical information about a model, such as its transparency, uncertainty, and input data. Social factors include the people, organizations, and relationships that shape one's trust of a model. These social aspects could include factors such as the credibility of the people or organization developing the model, reliability of the relationship with individuals recommending a model, or word of mouth within a community concerning a model's performance. Different factors may play greater or lesser roles in developing an individual's model trust process; therefore, these factors should be understood to facilitate appropriate calibration of individual trust.

**MODELS SHOULD HAVE THE CAPABILITY TO BE AS TRANSPARENT AS POSSIBLE; HOWEVER, NOT EVERY USER DESIRES FULL TRANSPARENCY. TRANSPARENCY SHOULD BE TAILORED TO THE NEEDS OF THE SPECIFIC INDIVIDUAL UNDER CONSIDERATION.**

Transparency involves how clearly one might assess a model's functions and understand how and why it operates as it does. This allows individuals to determine if the operation is appropriate for a decision at hand. Full transparency would involve having complete access to a model's code and documentation of the assumptions built within it. While there should always be the opportunity for full transparency, individuals may desire different levels of transparency. For example, high-level decision-makers may only desire transparency concerning high-level model assumptions because they lack the time or training to effectively investigate a model's code. Too much transparency could cause an information overload that obscures the relevant information. Conversely, others may desire the ability to be intimately acquainted with a model's workings. Transparency, therefore, should always be present, but should be tailored to the needs of the specific individual under consideration.

**APPROPRIATE MODEL TRUST CALIBRATION INCLUDES SHARING OF MENTAL MODELS BETWEEN ACTORS IN A DECISION-MAKING FLOW.**

A model is the explicit representation of the model developers' mental model of a situation. This mental model contains an implicit understanding of the capabilities and limitations of the model. The other individuals who interact with the model should calibrate their own mental models to that of the model developers, which includes developing an accurate understanding of the model's capabilities and limitations. Improperly calibrated mental models lead to inappropriate decisions on an individual basis, but as modeling is a sociotechnical process, improper mental models may also influence and hinder proper mental model development in other individuals within the flow of information.



**INCREASING THE SPEED OF DECISION-MAKING IMPLIES A DECREASE IN TIME SPENT ANALYZING A PROBLEM, WHICH IN TURN INCREASES THE CHANCE OF BIASED JUDGMENTS.**

Humans excel at pattern recognition and efficiently jumping to conclusions in the presence of limited information. These intuitive capabilities prove effective for many day-to-day activities, but they can also lead to systematic biases in certain contexts. Model-centric environments may seek to provide a more intuitive environment that users and decision-makers can directly interact with to build intuition and speed decision-making. However, these environments may make biases more likely by allowing users to quickly match patterns and move forward with incomplete, and potentially biased, understandings of a situation. Complex problems may require focused attention and analysis that take time to fully understand in order to develop an accurate mental model of the situation. While faster decisions are desired if they are effective, the speed itself may set people up for failure by encouraging them to rely upon their fast and intuitive, yet bias-susceptible, judgment, rather than the more cognitively demanding rational and analytical thought processes.

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**HEURISTICS AS PRACTICAL ENABLERS**

There are four application areas that have been proposed for the heuristics as practical enablers for model-centric engineering practice. These are: educating novices, conducting expert forums, conducting program team launches, and informing policy and practice.

**EDUCATING NOVICES**

A first application area is using the heuristics as part of basic education courses for model-based engineering, aimed at novices (i.e., individuals with relatively little engineering experience). Recent research studies show benefit of using heuristics to assist novice engineers in early design activities (Yilmaz et al., 2016; Murphy, et al., 2017).

Beginning engineering students may learn to use model-based toolsets quickly (having grown up using software applications); however, they lack the foundational knowledge behind the use of models in engineering decisions. By incorporating the heuristics into education modules and classroom exercises, they serve to amplify key learning points. Given that heuristics are concise statements, they have potential to make key points stick in the mind. Accordingly, they are useful for triggering class discussion. As an example, a teaching lesson on the importance of understanding context and assumptions could employ the following heuristic to initiate a discussion: **Models are created for specific reasons and context, and those assumptions fundamentally bound a model's applicability.**

A discussion on this heuristic may revolve around a model as insightful and valuable within one problem context, but the assumptions built into the model may not be valid within some other context. A key point is that evaluating a model's applicability should not just consider whether it has been validated, but in what contexts the model has been validated. Another useful

discussion point is that using a model outside of its inherent bounds leads to model results that are inappropriate for the problem under consideration. Specific case examples could be used to reinforce these points. Another use of a heuristic in education would be an assignment to write a short paper to elaborate on the heuristic.

### CONDUCTING EXPERT FORUMS

Enterprises undergoing transformation to model-centric engineering practice experience the challenges of re-orienting the workforce from traditional engineering to model-centric engineer. The more senior engineers with a long history of performing specification-based engineering are faced with doing things differently using modeling technologies and languages that are unfamiliar. These engineers can be challenged with making decisions with model-generated information in formats they perceive as not naturally comprehensible. This resistance to adoption of model-based engineering is cited as a challenge faced by leadership today (IAWG, 2017).

A factor that has major impact on engineering outcomes is the degree of trust in models. It is not that models are new for the expert workforce, but the changed manner and degree to which models are used in performing engineering tasks. In the future, models will be the “single source of truth” (Blackburn et al., 2015). The digital thread brings together models and communication mechanisms in a way in which they may not be aligned with the organization and traditional ways of doing things (West & Pyster, 2015).

There is potential benefit in the use of expert forums to gather together members of the expert workforce for dialogue on the changing landscape. This provides an opportunity to raise concerns, and through discussion promote understanding of the new landscape for performing engineering. Heuristics can be used in this way to trigger discussion among senior practitioners. The heuristics represent insights from an expert-level practitioner for example: **Increasing the speed of decision-making implies a decrease in time spent analyzing a problem, which in turn increases chance of biases judgement.** This heuristic could prompt meaningful discussion on the perceived value and risks of emphasizing efficiencies of models.

### CONDUCTING PROGRAM TEAM LAUNCHES

A third application for the heuristics is in conducting team launches at the start of a program or major phase on an ongoing program. A program team launch brings together the members of a team in a congenial forum to plan activities, assign responsibilities, and set team norms. Beyond practical planning, a team launch is meant to enhance trust and build collaborative spirit among team members. Using heuristics for launching a model-centric program is supported by Maier & Rechtin, who state they are “trusted, nonanalytic guidelines” and can be used “as aids in decision making, value judgements and assessments”. (Maier & Rechtin, 2009). Heuristics have potential to serve as a basis for an activity to set norms and team practices for the project. A common approach on a new model-centric program is to send all the engineers through tool training. Younger engineers may quickly learn to use modeling tools, but lack the experiential knowledge of engineering of products and systems. The members with years of experience, on the other hand, may find use of modeling software tools to be non-intuitive to

the point where they spend more time on tool mechanics and less on decision making. Any discomfort and distrust of models and modeling toolsets can have negative impacts on the engineering effort.

By using heuristics as “boundary objects”, there is an opportunity for team dialogue on how the project wants to employ models in context of the program and the competencies of the team members. An example of a useful heuristic for such a discussion is: **Models do not have agency – the ultimate responsibility for decisions must be upon the humans.** A team discussion on this heuristic could prompt discussion on the proper use of models in context of the specific program objectives, and how model-generated information is to be used by various team members on the project. Additionally, decision authorities and standard practices for documenting model-related decisions can be discussed and established. This heuristic can be used to invoke a discussion on what models will be used on the program, what decisions are expected to be informed by the model, and how model information is to be validated using expert review. Using a heuristic as boundary object encourages more open and non-confrontational discussion.

#### INFORMING POLICY AND PRACTICE

A fourth application of the heuristics is to support policy, practices and guidelines. As the heuristics are essentially encapsulations of expert strategies, they are useful for framing key points that can be elaborated in policy and practices that an organization develops. An example heuristic related to designing models for human use is: **Humans should not be forced to adapt to models, rather models should be designed for humans.** It suggests the need to have practices that identify capabilities to understand a model and identify mechanisms to ensure models generate information in a manner that it can be cognitively and perceptually processed by the model user (e.g., visualization enabling zooming to understand patterns in the data). Many organizations are revising engineering practices as part of the transformation to a model-centric enterprise. This heuristic could, for example, prompt a discussion on how to include the essence of the heuristic in evaluation of new models.

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#### DISCUSSION AND FUTURE DIRECTIONS

One limitation of the interview-based study was that it had a relatively small population size of thirty experts, with the majority coming from the aerospace and defense sector. Further, the subjects were primarily “through” actors. Additional study is necessary for more generalizable results, with inclusion of additional types of human actors in model-centric engineering and additional sectors.

Limited validation of the heuristics has been performed in the research to date. In the next phase, research will include iterative evaluation and refinement of heuristics from a larger pool of evaluators, in order to assess the heuristics as to their applicability and enhance potential acceptance. Endsley, et al. (2017) found that “a process of iteration through evaluation is effective for the creation of robust sets of heuristics for designers and evaluators”.

Planned future research will use the validated heuristics (guiding principles) as the basis for two pilot applications: (1) a teaching module for use in an undergraduate engineering leadership program and (2) a segment for use in a model-based engineering program team launch.

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## **SUMMARY**

The research has confirmed the need for further investigation on myriad topics related to human-model interaction. One is the need to formally capture the patterns of why, when and how various stakeholders use models. Studies and experiments are needed to better understand the most effective means and conditions for human interaction with models. Future plans include further investigation of knowledge from related fields. An important topic for future research is use of augmented intelligence in model-informed decisions. This includes understanding engineering tasks and decisions that necessitate human actors over automation, in context of the model-centric engineering effort.

## INTERACTIVE EPOCH-ERA ANALYSIS

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The Interactive Epoch-Era Analysis (IEEA) framework has been developed by adapting and extending the existing Epoch-Era Analysis (EEA) method through interaction and visualizations and associated infrastructure advancements. IEEA is proposed as an iterative framework for concept exploration that provides a means of applying EEA constructs while controlling growth in data scale and dimensionality. Further, IEEA leverages interactive visualization because prior visual analytics research has demonstrated that when performing exploratory analysis, like early-phase system concept selection, an analyst can gain deeper understanding of data which can lead to improved decision-making.

In Phase 3, the framework and supporting tools were applied to a multi-mission on-orbit servicing vehicle (Curry & Ross, 2016), demonstrating key concepts and prototype interactive visualizations, focusing on opportunities to improve the uncertainty analysis, ease of use, data scaling, visualization techniques, and overall analysis approach. In Phases 4 and 5, the research was applied to a commercial ship case to further test the framework and refine visualization prototypes (Curry et al., 2017). Discussion of the interactive prototypes can be found in the IMCSE prior phase report (Rhodes & Ross, 2016), with detailed implementation discussion in a recent doctoral thesis (Curry, 2017). An impact assessment experiment, initiated in Phase 4, aimed to decouple and evaluate the impacts of visualization and interaction on human performance. The experiment was completed in Phase 5.

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## BACKGROUND

While the transformation of engineering to a model-centric approach does involve some new frameworks, methods and tools, it does not involve abandoning those that are in use in engineering practice. Rather, there is a need to adapt the proven frameworks and methods for model-centric engineering. This includes the need to make these more interactive and extend them as needed to accommodate larger-scale problems and data sets. Similarly, there is a desire to make use of the latest research and approaches from data science and visual analytics in the extension of these existing frameworks, methods and tools. IMCSE has explored how an existing framework, Epoch-Era Analysis (EEA), can be adapted and extended in such a manner. Epoch-Era Analysis (EEA), supports narrative and computational scenario planning and lifecycle uncertainty analysis for both short run and long run futures. EEA is designed to clarify the effects of changing contexts over time on the perceived value of a system in a structured way (Ross & Rhodes, 2008). The base unit of time in EEA is the *epoch*, which is defined as a time period of fixed needs and context in which the system exists. This approach provides an intuitive basis upon which to perform analysis of value delivery over time for systems under the effects of changing circumstances and operating conditions, an important step to take when evaluating large-scale engineering systems with long lifecycles.

EEA has been applied in numerous case studies and in limited use in performing selected studies on real program studies. Some limitations in its application have been due to the large

scale of data sets generated in the engineering of complex systems. Because of the complex data that must be analyzed when extending EEA to large-scale problems, issues with cognition are introduced that may hamper decision-making. This motivates the need for extensions to EEA methods that overcome the computational and human cognition issues that may arise. It is hypothesized (Curry & Ross, 2015) that augmenting the traditional EEA approach with new analytic and interactive techniques will fundamentally enable new capabilities and insights to be derived from EEA, resulting in superior dynamic strategies for resilient systems. The Interactive Epoch-Era Analysis (IEEA) Framework has resulted from development, testing and refinement activities over the past several phases of research.

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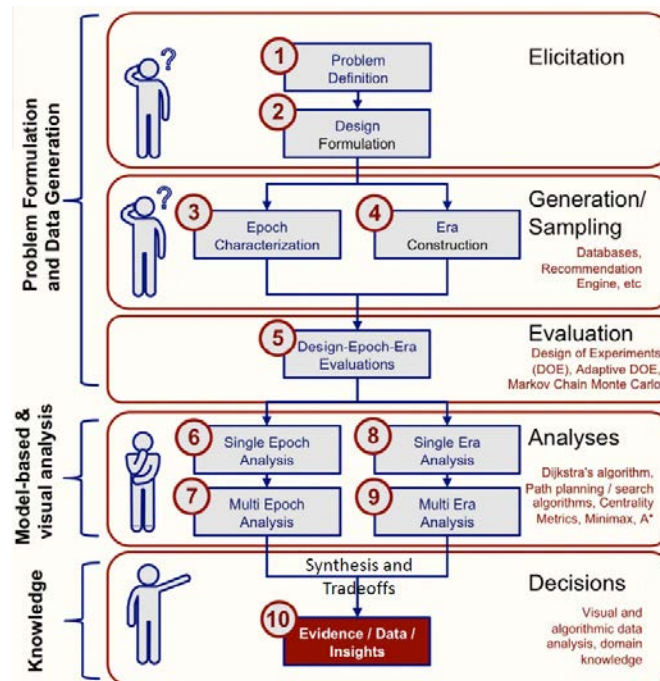
## IEEA FRAMEWORK

Interactive Epoch-Era Analysis (IEEA) leverages human-in-the-loop (HIL) interaction to manage challenges associated with the large amounts of data potentially generated in a study, as well as to improve sense-making of the results (Curry & Ross, 2015). Allowing the structured evaluation and visualization of many design alternatives across many different futures and potential lifecycle paths enables the design of systems that can deliver sustained value under uncertainty. Iteration is necessary because the analysis is inherently exploratory in nature. HIL interaction is necessary because the problem is not strictly deterministic or necessarily intended as a reliable prediction of system performance or future events. Often, there is both uncertainty and the potential for errors in assumptions or model implementation. This necessitates human judgment to make sense of the data; therefore, this is not by its nature a problem that can be handed over completely to an automated optimization algorithm, though some level of automated analysis could be beneficial as an aid to the user. Enabling users to interact with their data through visual interfaces of this type is an area of active research (Heer & Agrawala, 2007, Heer & Shneiderman, 2012).

### DESCRIPTION OF IEEA FRAMEWORK MODULES

The purpose of IEEA is to “guide the... practitioner through the steps of determining how a system will deliver value, brainstorming solution concepts, identifying variances in contexts and needs (epochs) that may alter the perceived value delivered by the system concepts, evaluating key system trade-offs across varying epochs (eras) to be encountered by the system, and lastly developing strategies for how a designer might develop and transition a particular system concept through and in response to these varying epochs”. To that end, the IEEA framework, as shown in Figure 5, is characterized by 10 individual processes that can be abstracted into five main modules:

1. **Elicitation** of relevant epoch and design variables (often through interview),
2. **Generation/Sampling** of all epochs, eras and design tradespaces (often including enumeration) in which to evaluate design choices,
3. **Evaluation** of designs in sampled subset(s) of epochs and eras
4. **Analyses** of design choices in the previously evaluated epochs and eras, and finally
5. **Decisions** of final designs based on iterative evidence from previous modules.



**Figure 5. Interactive Epoch-Era Analysis Framework**

While the sequence of these modules flows logically, IEEA is intended to be an iterative process where users can go back and change responses within earlier modules at any point to reflect what they have learned from later ones. The five modules are composed of the 10 processes, but depending on the nature of the study and the type and fidelity of information available to the analyst, it is not strictly required that each process step be employed. From a computing infrastructure perspective, many of the techniques discussed in Curry et al. (2015) can be applied to augment and facilitate a practical implementation of the workflow. For example, online analytical processing (OLAP) techniques may be applied to improve data handling, and search algorithms may improve our ability to offer more informed recommendations to decision-makers during the epoch-era analysis. Similarly, enhanced human interaction techniques and visualizations may aid in the analyses of the vast amounts of information required to reach an informed decision.

## DEMONSTRATION OF INTERACTIVE VISUALIZATION

The IEEA framework research furthered understanding of the use of interactive visualizations in complex engineering system studies. The visualization prototypes were developed based on prior relevant research, and with continuous feedback using informal review from subject matter experts.

## PRIOR RELEVANT RESEARCH

Effective analysis of EEA generated data to derive valuable insights enables analysts to make informed decisions and design successful strategies for value sustainment. Techniques from

visual analytics are central to IEEA, as evidenced by their successful application in other domains to solve real-world problems. Visual analytics applications are beneficial for addressing problems whose size, complexity, and need for closely coupled human and machine analysis may make them otherwise intractable (e.g., Chang et al., 2007). An example is the creation of a visual analytics application for detecting financial wire fraud (Yang et al., 2008). In banking, the nature of fraud is ill-defined and constantly evolving, much like the nature of value among different decision makers in system design. A similar comparison can be made with recent visual analytics applications in the field of healthcare that must also frequently contend with ill-defined problems. The same data, explored by different medical professionals can lead to different decisions for a variety of reasons including risk aversion, available resources, or experience-level (Caban & Gotz, 2015). Additional examples can be found in such diverse domains as infrastructure maintenance (Wang et al., 2010) and understanding the nature of global terrorism (Chang, 2008). Clearly many other large-scale problems have seen significant benefits by coupling skills of subject matter experts with well-developed visual analytics applications that help them consider and comprehend complex data.

Visual analytics extends beyond traditional scientific visualization and focuses on extracting insights from data using interactive visual interfaces (Wong & Thomas, 2004). Interactive visualizations are used to integrate a user's knowledge and inference capability with numerical and algorithmic data analysis processes. Thomas & Cook (2005) presented the first widely accepted roadmap for visual analytics research in their seminal book. As they described, the research agenda in this field seeks to develop "the science of analytical reasoning facilitated by interactive visual interfaces". Keim et al. (2010) updated the roadmap and provided the following revised definition of visual analytics: "Visual analytics combines automated analysis with interactive visualizations for effective understanding, reasoning and decision making on the basis of a very large and complex dataset". Icke (Icke & Sklar, April 16, 2009), Keim (2010), Keim et al. (2010) and Sun et al. (2013) provide good overviews of the state of current research on visual analytics. While there are obviously many different areas of investigation ongoing in visual analytics research there are three particular areas that are highly relevant to the current effort for IEEA: (1) methods to facilitate user interaction with data; (2) specific types of visualizations and frameworks; and (3) data reduction and handling of large amounts of data.

Visual analytics research on methods for interacting with data to extract useful insights provides some guidance to the current research on IEEA. As a visual metaphor for describing how data interaction should be applied to gain insights, Shneiderman et al. (1996) proposed the famous information seeking mantra: "Overview first, zoom/filter, details on demand". Highlighting the need for coupling numerical and algorithmic data analysis with interactive visual interfaces to gain insights during visual data exploration Keim et al. (2006) later extended the mantra. The revised version called the visual analysis mantra was: "Analyze first, show the important, zoom/filter, analyze further, details on demand". Prototype applications for IEEA follow the visual analysis mantra as a guideline.

The visual analytics process introduced by Keim et al. (2010), as shown in Figure 6, is characterized through interaction between data, visualizations, models of the data, and the



users, in order to discover knowledge. The process, shown, begins by transforming the data (e.g. filtering, sampling, cleaning) so that it can be analyzed further. Next, visual or algorithmic analysis methods are applied to explore the data. When visual data exploration is used, users directly interact with the visual interface to analyze and explore the data. When automatic analysis methods are applied, approaches such as regression modeling or pattern matching are used to estimate models for characterizing the data.

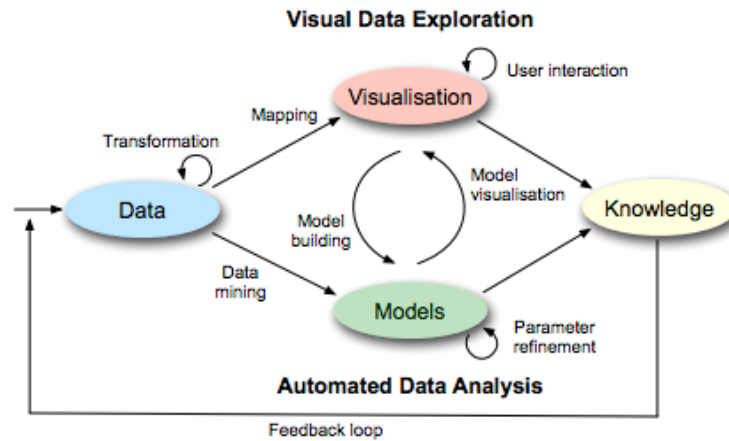


Figure 6. Keim et al. (2010) on Solving Problems with Visual Analytics

Numerous frameworks for developing interactive visualization applications exist. Prototype applications for IEEE utilize prior research on Data-Driven Documents (D3), a representation-transparent framework for rapid development of online data visualizations developed by the Stanford Visualization Group (Bostock et al., 2011). D3 is used for producing dynamic, interactive data visualizations in web browsers and is the successor to earlier work on the Protovis framework (Keim et al., 2010; Bostock & Heer, 2009). It allows for direct manipulation and modification of any elements in the document object model (DOM) and enables smooth animation and user interactions.

Several other concepts from research within the visual analytics community are also relevant to the current research on IEEE. Data reduction techniques like those described by Fodor (2002, Holbrey (2006) and Liu et al. (2013) are necessary because computational resources will always be a constraint on complex decision problems like those encountered in systems engineering analysis. Problems arise in computing, storing, and transmitting the data from a database or local storage device to the user display. Several researchers have also focused on the problem of how to visualize large sets of data once they reach the user display (Inselberg, 2000; Andrews, 1972), Ankerst et al., 1998; Delorme & Makeig, 2004). Others have focused more on the specific types of visualizations such as scatter plots, tree maps and parallel coordinate diagrams (Chi, 2000; Cleveland & McGill, 1984; Carr et al, 1987; Inselberg & Dimsdale, 1990; Keim, 2000).

The background provided by this prior work is extremely important to solving the problem at hand, but Curry (2017) argues that for decision making in systems engineering applications the

most important factor is arguably whether the decision maker understands and can find insights in the multi-faceted data they are viewing. Recent work on multiple coordinated visualizations has been geared towards determining how user displays with multiple types of information can be used to extract deeper meaning from the data (Roberts, 2007; Scherr, 2008; Andrienko & Andrienko, 2007). This is a potentially useful technique for the types of systems engineering interfaces that are prototype applications generated for this research.

Many engineers make decisions about constraints on performance parameters (outputs) without considering how that restricts ranges on design variables (inputs). As an example, if an engineer sets a resolution requirement on a satellite that requires a certain optical aperture size, this will likely restrict the set of available launch vehicles that can take that satellite into orbit due to fairing size restrictions. Supplying the engineer with immediate visual feedback on the consequences of their decisions could be enabled through simultaneous coordinated views of both the design and performance spaces. Curry (2017) points out that enabling users to interact with their data through visual interfaces of this type is an area of active research. Integrating data interaction, algorithmic analysis and advanced engineering methods are important aspects for current research effort on IEEEA.

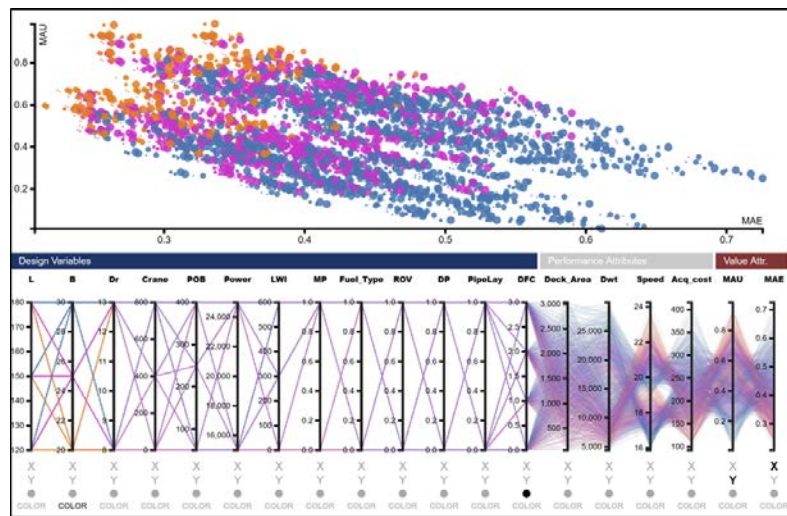
#### **INTERACTIVE VISUALIZATION FOR INTERACTIVE EPOCH-ERA ANALYSIS**

The research on interactive visualization in context of epoch-based analysis allowed for exploration and demonstration of what is possible; refinement of the existing visualizations and development of new ones is necessary for real-world application. Additional expert review and more extensive user testing on real-world applications would likely generate new ideas for customized visualization types and interaction methods. Scalability of existing visualizations requires further work, such as more scalable versions of parallel coordinate diagrams and force directed graphs. Future research on development and use of new interface types such as touch interfaces and distributed mobile platforms is also needed.

Curry et al. (2017) and Curry (2017) provide details on the visualization prototypes that were explored in the IEEEA research. The interactive visualization capability is intended to provide a means for decision-makers to interactively evaluate the performance of multiple design alternatives across multiple futures. Such capability creates opportunities for new insights at the expense of a potentially large and complex data set that can be difficult to analyze. The application of an interactive framework allows the users to visualize and engage with the data in new ways that can facilitate improved comprehension and decision-making. The insights that are extracted from this approach allow decision-makers to understand the characteristics of designs that can sustain value in all possible futures, through passive robustness or active changeability.

An example visualization for IEEEA single epoch analysis is comparable to what is often referred to in practice as tradespace exploration via scatterplots. Within a given epoch, a scatterplot of cost (MAE) versus benefit (MAU) can be constructed that is fixed for short-run periods of stable context and needs (i.e., an epoch). Typically, decision-makers want to identify the frontier of Pareto optimal designs or, more generally, designs that are “close enough” to the Pareto front. Here the notion of “close enough” is operationalized through Fuzzy Pareto Number (FPN) which

is used to quantify distance from the Pareto Front for each design in each epoch. FPN is a “within-epoch” metric and its score for a given design will change from epoch to epoch. Decision-makers can gain insights regarding difficulty of a particular set of context and needs by visualizing how points move in the design space as the epoch and FPN values change. Additional insights may be gained from interactively filtering the design, performance, or value variables. This can be performed with aid of a filtering application to allow decision-makers to interact with data to identify designs and epochs of interest (Figure 7). It allows them to assign any of the defined variables to the radius, color or x-y location of the points in the scatter plot to explore the data in four dimensions to better comprehend the behavior of the designs.



**Figure 7. Interactive Filtering Application for tradespace exploration for the offshore ship design base case**

Figure 7 illustrates the tradespace for the offshore ship design base case that is the targeted contract with no technical requirements. Hence, at this initial stage, one can focus on understanding the dynamics of the underlying system. In this particular case study, the MAU degenerates into a single attribute utility function, which is a function of eco-friendliness, even though the figure indicates a multi-attribute utility function on a general basis. The interactive filtering can aid in visualizing the exploration process of understanding the relative significance of individual design variables, as illustrated. For instance, filtering by beam and length, one can see that relatively slender ships tend to contribute to low FPN values. However, this again makes a design less stable in the water, which restricts the possibilities of retrofitting heavy equipment on deck without intervening with the main hull. Further, one can directly see the trade-offs of adding “design for changeability” (DFC) levels, as design points shift right in the tradespace with increasing DFC due to increased cost. (DFC level is a proxy for degree of modularity and ability to more easily change the ship; operationalized with impacts on structural mass and interfaces.)

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## DEMONSTRATION CASES

The IEAA framework was tested and refined using two demonstration case studies: (1) Space Tug, a multi-mission orbital transfer vehicle; and (2) Commercial Offshore Ship.

### SPACE TUG ORBITAL TRANSFER VEHICLE

Application of IEAA to a case study for a multi-mission on-orbit servicing vehicle demonstrates key concepts and prototype interactive visualizations. A space tug may be used for a variety of missions including observing, servicing or retrieving on-orbit spacecraft. The original case study described by McManus & Schuman, 2003) is, at first glance, a seemingly simple trade study, but despite the simplicity of the system model the analysis is actually nontrivial. Fitzgerald (2012) expanded upon this case as a demonstration of his valuation approach for strategic changeability (VASC). The case study demonstrated in this IMCSE research, replicates the one by Fitzgerald, which provides for an interesting comparison since the application of IEAA leads to different insights that impact previous conclusions. Various visualization prototypes were developed and tested in this case. Application of IEAA to the case study for a multi-mission on-orbit servicing vehicle demonstrates key concepts and prototype interactive visualizations (see Curry & Ross, 2016 for a detailed description of the case).

### COMMERCIAL OFFSHORE SHIP

This case applies the Interactive Epoch-Era Analysis (IEAA) framework on a case study from commercial offshore ship design, incorporating techniques from visual analytics such as interactive visualizations to gain insight from large, high-dimensional data sets resulting in improved strategies for value sustainment. This case study is based on a commercial ship case, developed by Rehn et al. (2016); a more detailed discussion of the case setup is provided in that paper. Offshore ships, in contrast to traditional deep-sea cargo ships, are designed to provide special operational services typically related to the offshore oil and gas industry.

A discussion of the case, with prototype application examples and discussion of the capabilities and insights, can be found in Curry et al. (2017). The new prototype visualizations described are motivated by a need to address design questions that are not well-suited for analysis with metrics alone, often applied in other EEA case studies, such as Fuzzy Pareto Number (FPN) or Fuzzy Normalized Pareto Trace (fNPT). For the offshore ship design case, this includes assessing the trade-off between designs optimized to target the primary mission versus being robust for uncertain subsequent missions. Further, considerations related to the implementation of interactive visualization applications, such as scalability and latency, are discussed emphasizing a need for continued research on methods for effectively handling large, high-dimensional data sets in design of complex systems under uncertainty.

Figure 8 illustrates a single epoch analysis interactive, linked visualization. The goal of this visualization is equivalent to traditional tradespace exploration: find the Pareto efficient solutions, gain situational awareness of tradeoffs, on an epoch by epoch basis (here 96 epochs, with 41,204 designs in each). Figure 9 illustrates a multi-epoch analysis interactive, linked visualization. The goal of this visualization is to identify designs that do well ACROSS the epoch

space (i.e. robust) through either passive (versatility) or active (changeability) means. Over 4 million data points are abstracted in this visualization, embodying the “show the high level” part of the visual analytics mantra. Figure 10 illustrates a second multi-epoch analysis interactive, linked visualization. This one embodies the “zoom, filter” part of the visual analytics mantra. Whereas the prior visualization enabled a situational awareness of the data, this one allows for diving deep into the details, in particular using filters to determine which active or passive means relate to the achieved robustness across the epoch space. The implementation leverages both OLAP and binned aggregation to enable real time (i.e. low latency) interaction. The 4 million data points have been reduced to ~40 thousand via the aggregation. Figure 11 illustrates a single era analysis interactive, linked visualization. The goal is to evaluate the value of design-strategy pairs for sequences of future epochs. A *strategy* defines how change options will be used to sustain value (e.g. maximize utility or efficiency). The coordinated visualization allows for interactive filtering based on five era-level metrics that evaluate temporal aspects of value delivery (i.e. the “shape” of the value over time curve, the aspects of which may matter differently to different stakeholders; e.g. slope, volatility, etc.)

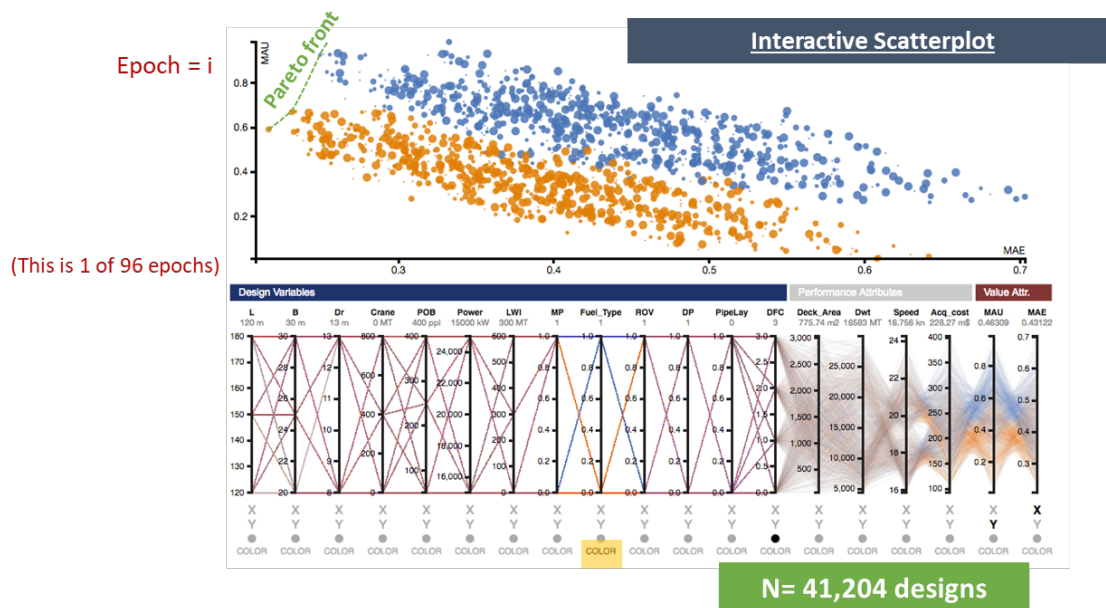


Figure 8. Single Epoch Analysis (within context/needs) example visualization for offshore case

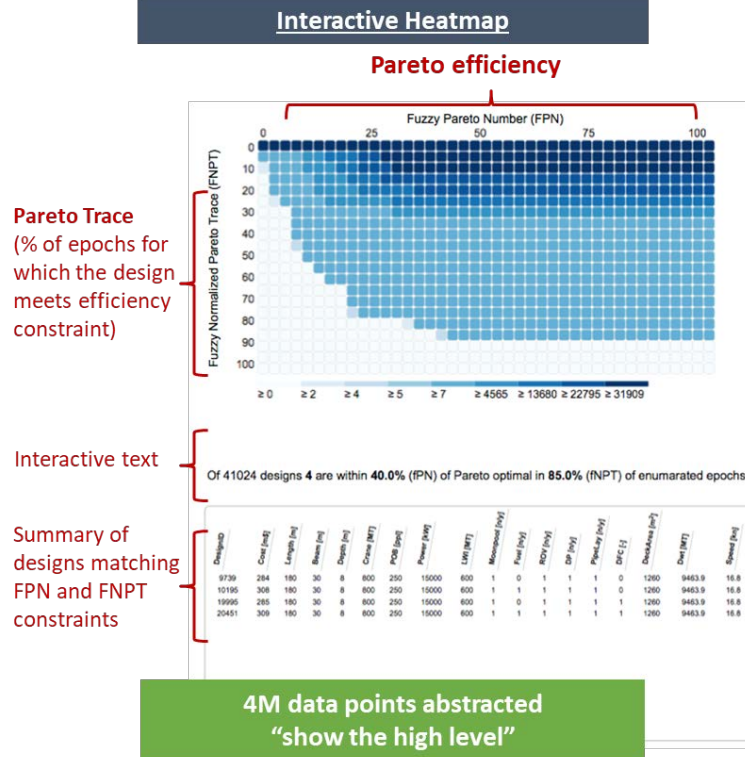


Figure 9. Multi Epoch Analysis (across context/needs) “show the high level” example visualization for commercial offshore case

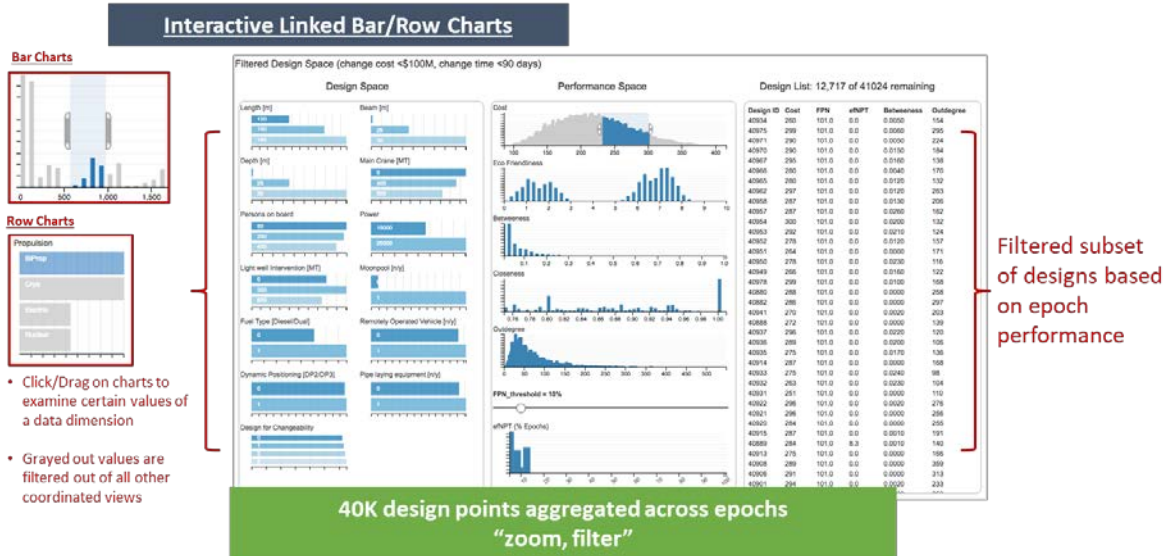
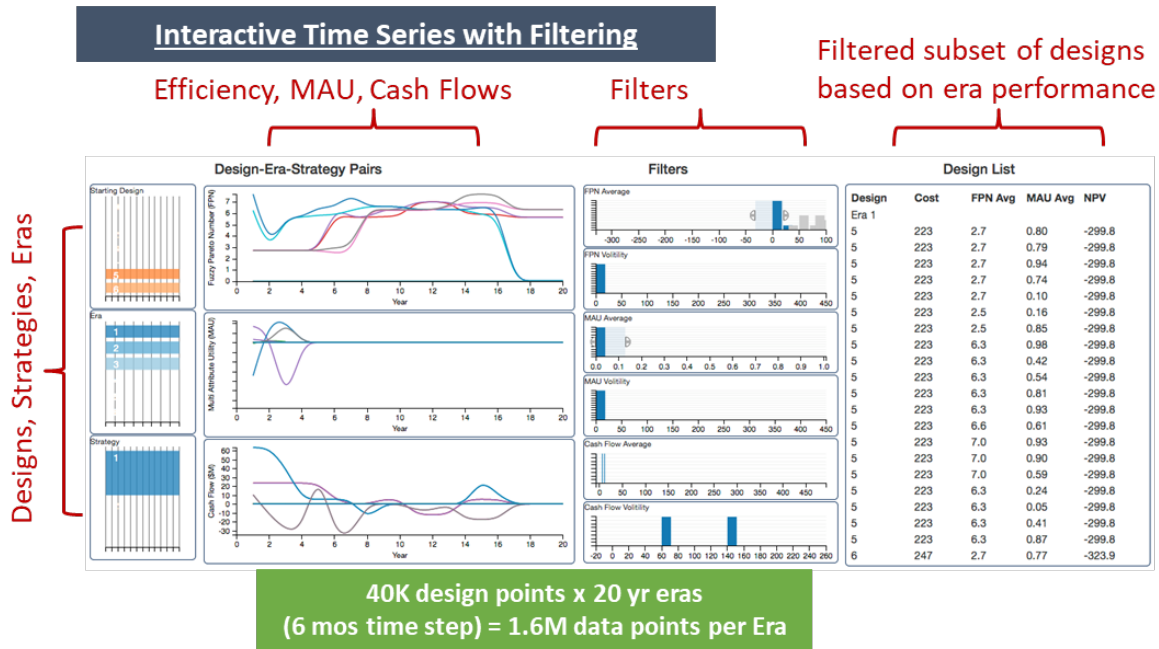


Figure 10. Multi Epoch Analysis (across context/needs) “zoom, filter” example visualization for commercial offshore case





**Figure 11. Single Era Analysis (across time) example visualization for commercial offshore case**

Insofar as generalizability of the results, these techniques and visualizations (albeit some degree of visualization customization is ALWAYS needed) can be used to evaluate the attractiveness of modularity in acquisition. In particular, modularity is an enabler for reducing the switching cost of a system between alternative design or operational states. This reduced switch cost comes at the expense of increased design costs and carrying costs (e.g. the interface infrastructure may entail increased physical mass, power, and structural integrity than a non-modular interface). Additionally, the cost of developing and maintaining a set of modules to be available when needed must be addressed. IEAA can be used to not only provide a framework for including both modular and non-modular solutions for comparison within a tradespace (which helps to assess the lay-in, opportunity, and carrying costs of modularity), but also a means for determining the costs and benefits of having the option to switch between states (e.g. swapping a mission payload or manufacturing line). Agility is related to the speed by which a system can respond to the (potential) impact of a disturbance. Modular approaches may reduce the switch time and cost of response, but the particulars of the module options, as well as needed changes in the underlying system and its enterprise should be evaluated to have the proper scope of tradeoffs considered. As far as implementation specifics, both modular and non-modular design options would populate the tradespace, and module swapping “options” would be implemented as change rules/mechanism that would transform the tradespace into a tradespace network. The multi-epoch analysis would enable determination of which modules are most attractive in which epochs. Era analysis would enable evaluation of the timing aspect (i.e. via strategies determining when “to switch” or “not to switch” and how the costs and benefits of those would relate to a degree of agility in the system).

Over the course of the research it was found that in spite of wide consensus in the literature that interactive visualizations enable human performance gains, there were no primary sources providing evidence that supports this “generally recognized as true” claim. Therefore, in order to have some amount of evidence supporting this basic claim, which is needed for this research, a controlled human subjects experiment was designed to assess whether interactive visualization improves user performance for design problem tasks. A primary working hypotheses of this research is that the creation of visual analytic applications that couple interactive visualization with design methods (like Epoch-Era Analysis) will benefit human performance. Accordingly, this experiment (introduced in the prior phase research report) required subjects to answer questions related to a simplified engineering design problem equivalent to a multi-epoch analysis problem. Subjects were randomly assigned to one of four treatment groups that were distinguished by the type of data representation or analysis tool they were given to solve the problem. It was anticipated that both the treatment group and individual differences between subjects impact performance as measured by task completion time and accuracy. Individual differences as discussed in this study refer to the subjects’ personality traits and spatial reasoning ability. Results of the experiment confirm that this is indeed the case and that performance further relates to the task type in question. The question under consideration in this experiment is: *Does interactive visualization improve user performance for design problem tasks and, if so, what are the relative contributions of representation, interaction or other factor to user performance?*

There are two components to this question that must be tested. First, is there any measurable impact on human performance when individuals are engaged in performing analysis tasks commonly associated with engineering system design problems? Second, can the degree to which interaction, visualization or other factors, such as individual differences in the users, affect human performance be isolated and identified. For the purpose of this study human performance is measured in terms of both the speed and accuracy with which a subject can complete a relevant task. A primary working hypothesis of this research is that interactive visualization will improve design task performance for either, or perhaps both, of these metrics, and visual representation and interaction with data used to complete the task will impact performance in different ways. To decouple the relative contributions of representation and interaction a 2-by-2 factorial experiment with a total of 4 treatment groups was designed. Each treatment group corresponds to a different analytical tool that is provided to test subjects to complete a design task. All subjects were randomly assigned to a treatment group and asked to perform analyze a surrogate design problem, comprised of several tasks, that is a simplified version of a multi-epoch analysis problem. Because individual differences in personality or spatial reasoning ability may also play a role in task performance, data regarding these factors is also collected from participants using a pre-test.

A controlled human subjects experiment was deemed an appropriate and effective approach for testing the working hypotheses. By controlling for whether or not a subject is given a data visualization and/or an interactive capability designed to aid them in solving a particular task

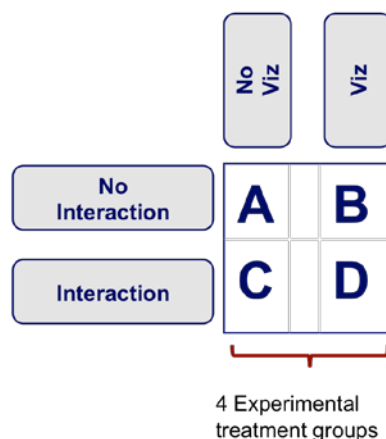


the factors most influential to performance can be isolated. While the individual differences of the subject volunteers cannot be controlled this experiment can still effectively measure the impact of these factors by collecting a large and diverse sample set of participants.

The participants in this study were drawn from volunteers using Amazon's Mechanical Turk (MTurk) online crowdsourcing marketplace. Crowdsourcing the evaluation of interactive data visualizations is an attractive option because of its convenience, ease of scalability to large numbers of participants, and relatively low cost. Previous research studies have assessed the viability and validity of using MTurk for these types of studies and provide guidance for its application (Heer & Bostock, 2010). Several other studies dealing with visualization and human performance have also shown that MTurk subjects can generate positive results (Ziemkiewicz, 2013; Brown, et al., 2014; Ottley et al., 2015; Micallef et al., 2012).

### TREATMENT GROUPS

The two primary controlled variables in this experiment were the presence or absence of (1) an abstracted representation of the data (e.g. chart, graph, visualization) and; (2) an interactive capability for manipulating or engaging with the data in some way (e.g. filtering, sorting). It was hypothesized that these two things could aid a subject's understanding of a problem differently. To decouple relative contributions of representation and interaction, a 2-by-2 factorial experiment with a total of 4 treatment groups was designed. Each treatment group corresponds to a different analytical tool provided to test subjects to complete a design task. **Figure 12** summarizes the four analytic tools subjects received as treatments in this experiment.



**Figure 12 Experimental Treatment Groups**

Subjects were randomly assigned to one of these four treatment groups, but each was given identical tasks and questions to answer.

### TREATMENT A: NON-INTERACTIVE TABLE

This group can be considered the control or standard treatment group in this study. Subjects are given a non-interactive table on the screen (Figure 13) that they must scroll through to determine the answer to task questions.

design ID	cost	reliability	mpg	top speed	0% compromise	5% compromise	10% compromise	15% compromise	20% compromise
1	4200	77.1	22.2	89	0	1	2	3	3
2	4050	76.2	20.4	92	0	1	2	3	4
3	4250	79	23.3	88	0	1	2	3	3
4	3500	60	27	81	4	4	4	4	4
5	3550	67.6	17.2	88	2	4	4	4	4
6	3700	76.2	18.2	82	1	2	4	4	4

Figure 13. Treatment A - Non-Interactive Table

#### TREATMENT B: NON-INTERACTIVE TABLE + VISUALIZATION

This group extends the tool used for treatment A to include a non-interactive static graph. The graph is a stacked and grouped bar chart, as shown in Figure 14. Error! Reference source not found..

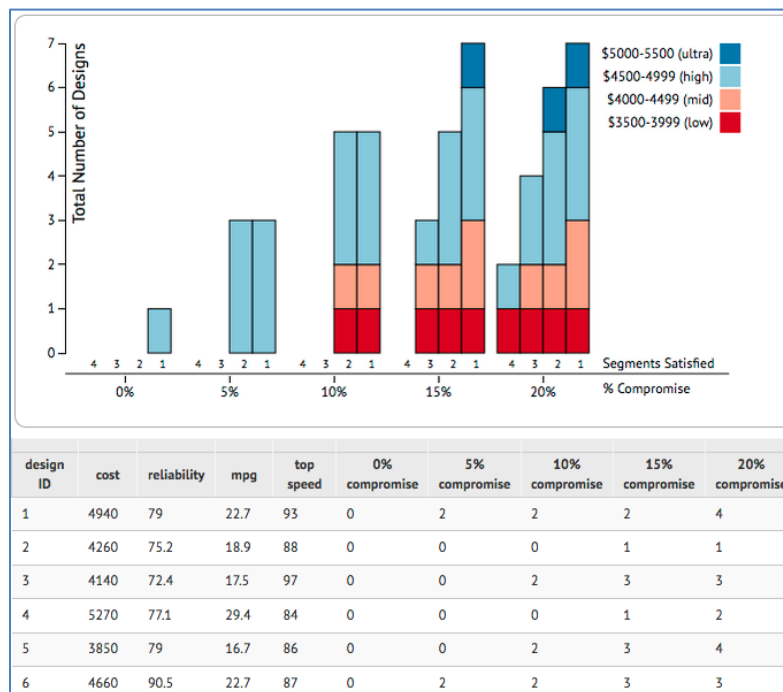


Figure 14. Treatment B - Non interactive Table + Visualization

#### TREATMENT C: INTERACTIVE TABLE

This group extends the tool used for treatment A to include an interactive capability as shown in Figure 14. A row of input boxes above each column allows regular expressions (e.g. " $\leq 20$ ") to be entered to filter the data set. Clicking on the column headers allows the data to be sorted by each data dimension.

Number of Designs: 100									
design_id	cost	reliability	mpg	speed	0% compromise	5% compromise	10% compromise	15% compromise	20% compromise
1	4200	77.1	22.2	89	0	25	50	75	75
2	4050	76.2	20.4	92	0	25	50	75	100
3	4250	79	23.3	88	0	25	50	75	75
4	3500	60	27	81	100	100	100	100	100
5	3550	67.6	17.2	88	50	100	100	100	100
6	3700	76.2	18.2	82	25	50	100	100	100

Figure 15. Treatment C - Interactive Table

#### TREATMENT D: INTERACTIVE TABLE + VISUALIZATION

Treatment group D combines the interactive filtering and sorting capability of group C and an interactive bar chart similar to the static bar chart in treatment group B, as shown in Figure 16.

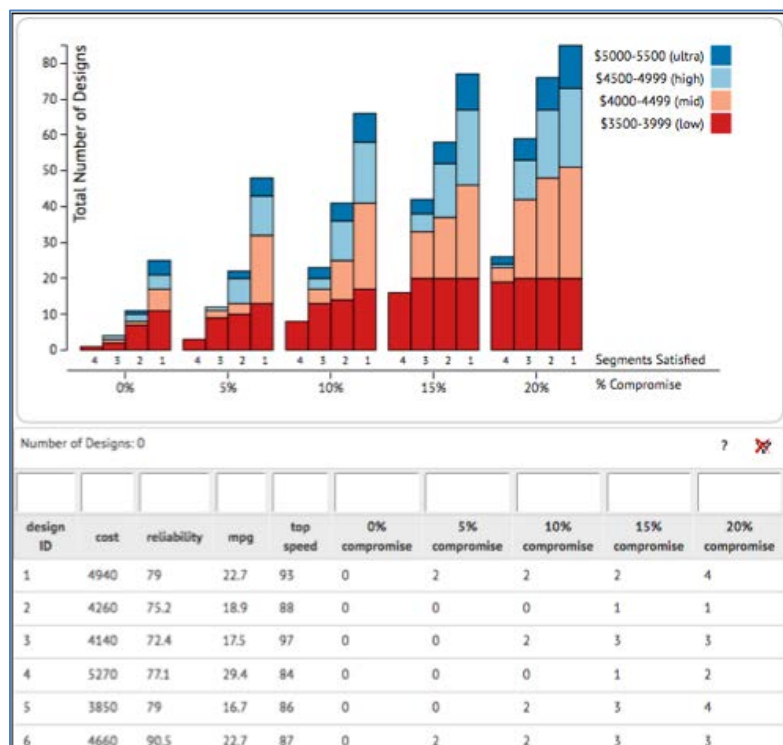


Figure 16. Treatment D – Interactive Table + Visualization

#### TRIAL PROTOCOL

Participants were asked to complete a 3-part evaluation. The first part of this study asks participants to complete a standard test of spatial ability called the "Paper Folding Test". The second part of the study asks participants to complete a survey that evaluates the standard Big 5 Personality traits and locus of control commonly used in social science research studies. The third part of the study asks participants to answer several questions about surrogate

engineering design tasks using one of 4 possible web-application interfaces depending on which experimental treatment group they have been assigned into randomly.

The possible interfaces are either:

- (A) a plain text table of data;
- (B) a static graph or visualization of the data;
- (C) a Microsoft Excel-like interactive table of data; or
- (D) an interactive visualization of the data.

Participants may exit the study at any point. Data from participants that exit the study early will not be included in the final analysis. The trial protocol is shown in Figure 17.

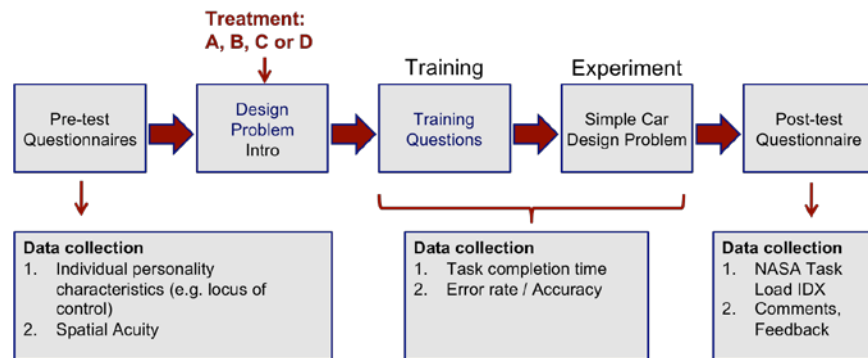


Figure 17. Trial Protocol

### EXPERIMENTAL TASK

In the experimental task, participants were asked a series of 9 questions about the design problem they are given. The amount of data required to answer questions varied so that the impacts of overloading a subject's working memory could be assessed. Questions were defined by 3 different task types: (1) Filter tasks ask users to identify or count some subset of the data points; (2) Sorting tasks require data to be ordered numerically or alphabetically to answer the question; and (3) Trend task require the identification of a pattern in the data across groups or categories. After completion of the 9 questions related to the surrogate design task the final question of section 3 asked subjects to rate their perceived workload while performing tasks.

### FINDINGS

This experiment was conducted to better understand if interactive visualization improves decision-making for design problems involving complex systems tradeoffs. The experiment collected data from human subjects working with various web-based design tools to perform a surrogate design tasks for a simplified car design. A total of 104 subjects participated in the experiment, with 26 participants per treatment group.

By controlling variables associated with the type of interface provided, the experiment allowed the impacts of visualization and interaction on human performance to be decoupled and evaluated. Additional detail about how individual differences, such as subjects' personality and spatial reasoning ability, influence results were evaluated using data collected from pre-test questionnaires. A summary of experiment results by treatment group is shown in Figure 18.

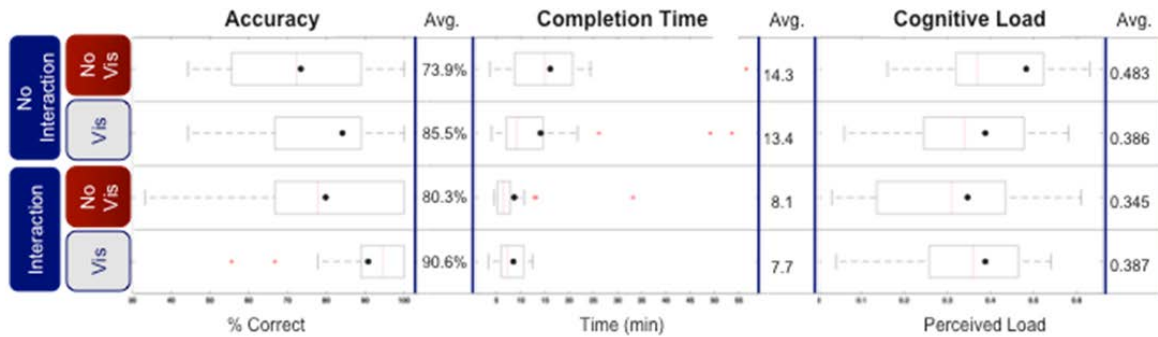


Figure 18. Summary of experiment results by treatment group (source: Curry, 2017)

Curry (2017) enumerates several conclusions that can be drawn from the experimental results about the impact on task accuracy, completion time and cognitive load.

### Task Accuracy

- The type of interface used to answer design task questions influence task accuracy. Specifically, adding a graph improves accuracy on trend observation tasks and adding an interactive capability improves accuracy on sorting tasks.
- Presence of a graph or interactive capability becomes more important as the number of data points associated with the task increases.
- Accuracy is strongly correlated to an individual's spatial reasoning ability when either a graph or interactive capability is present.

### Completion time

- The effects of adding a graph are small, but adding an interactive capability significantly reduces the time required to solve design task problems. This effect is most prominent on tasks that have 25 or more data points associated with them.
- There is no clear correlation between task completion time and individual personality characteristics.

### Cognitive Load

- Adding a graph or interactive capability reduces cognitive load, but adding both does not further reduce the perceived load.
- Reported drops in mental and temporal demand as well as lower levels of frustration are the primary drivers of reduced cognitive load.
- Cognitive load has a strong negative correlation with spatial reasoning ability. As spatial reasoning ability increases cognitive load decreases significantly. This correlation is even stronger when an interactive capability is available.

The human-in-the-loop experiment demonstrates the relative contributions of the two primary components of visual analytic systems (representation and interaction) and how they are impacted by factors such as task type, data volume and individual personality differences. Because the surrogate design problem used in the experiment closely mirrors the challenges of an actual multi-epoch design problem the results can offer guidance on how the interactive

applications for IEEA should be constructed (e.g., knowing how the objective of a given task maps to the type of element (e.g. graph, table); the nature of the assistance the application is expected to provide). Further, this experiment also shows that improvements in accuracy are strongly correlated to subjects' spatial reasoning abilities, but improvements in task speed are not. Knowing that an individual's innate characteristics are relevant to their performance opens up possibilities for pre-screening users or, alternatively, providing targeted assistance by allowing interactive applications to adapt to their user. The results of this experiment demonstrate the potential benefits that IEEA applications can provide and may also improve future interactive applications intended for engineering system designers.

Further details of the study, analysis of data, limitations, and findings are available in (Curry, 2017). Future research is suggested in regard to additional development of interactive visualizations, adaptation of visualization applications to individual differences, and backend/computing related techniques and tools.

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## **SUMMARY**

Phase 5 built on prior phase work, testing and refining the Interactive Epoch-Era Analysis (IEEA) framework, aimed at providing a means for analyzing lifecycle uncertainty when designing systems for sustained value delivery. The framework was tested on two demonstration cases: an on-orbit space vehicle case and a commercial offshore ship case. The two cases served to demonstrate key concepts and prototype interactive visualizations. The latter case included deeper analysis of options at the epoch-level for changeability as well as era-level analysis of time-dependent aspects of system value (Curry & Ross, 2017). A human-in-the-loop impact assessment experiment that decoupled interaction and visualization was completed, with a total of 104 subjects. The experiment resulted in several conclusions concerning the impact of interaction and/or visualization on task accuracy, completion time and cognitive load.

## MODEL CURATION

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The January 2015 IMCSE Pathfinder Workshop participants cited model curation as an important topic for investigation in evolving model-centric engineering (Rhodes & Ross, 2015). As engineering practice becomes increasingly model-centric, models are valuable assets for designing and evolving systems. New leadership roles and responsibilities become necessary in model-centric enterprises.

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### BACKGROUND

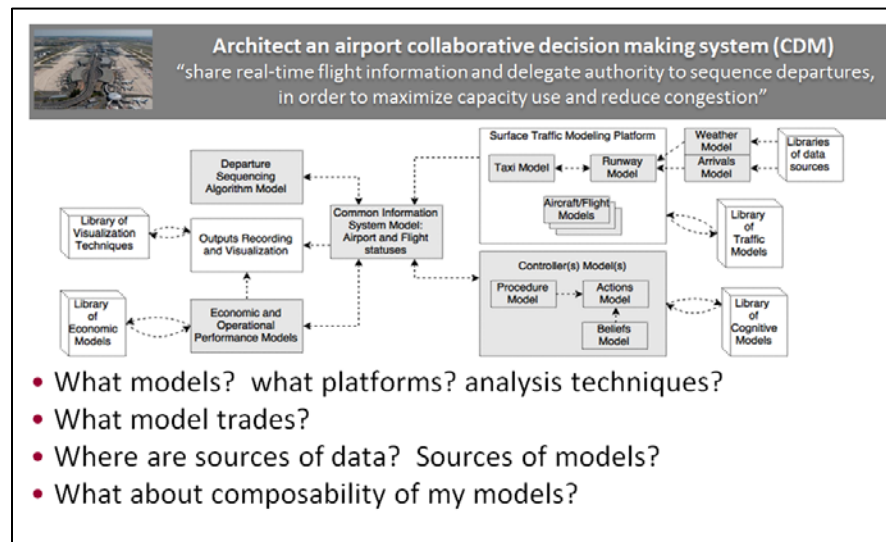
Reymondet et al. (2016) investigates considerations for curation in the engineering of complex socio-technical systems. As engineering practice becomes increasingly model-centric, models are valuable assets for designing and evolving systems, and continue to exist throughout the lifespan of a program, making the management and control of models and digital artifacts imperative. Maturing an approach for model curation in the systems engineering field can leverage work of other curation practices in other fields.

The National Academies performed a study and published a report on digital curation, stressing the importance of “active management and enhancement” and discussing the importance of preparing the workforce (NAS, 2015). According to that report, digital curation is unique in that “the immense and ever-increasing quantities of material to be curated, the need for active and ongoing management in a context of continually changing uses and technology, and the great diversity of organizational contexts in which curation occurs”. Social curation is also a relevant area that focuses on collaborative sharing of Web content organized around one or more particular themes or topics. Duh et al. (2012) define social curation as “the human process of remixing social media content for the purpose of further consumption”. Patel et al. (2009) examined curation of CAD engineering models, noting some specific challenges. The first is that “the information to be dealt with are diverse and particularly complex, including product geometry, finite element analysis models, manufacturing process models, etc.” Another challenge is engineering organizations need to communicate that information to a wide range of different stakeholders, each with different information needs and access rights”. They note that the purpose of the information may be varied. Their work is primarily focuses on technical strategies for curation; but also say “there is a need for best practice guidelines and cost-benefit models to aid in choosing appropriate curation strategies since the business of deciding a suitable path is non-trivial and contingent on many factors” (Patel et al., 2009).

As digital transformation progresses, model-centric enterprises need to re-examine the leadership roles and responsibilities that will enable digital model-based engineering practice. A study by the US Interagency Working Group describes seven challenges that organizations may encounter in infusing digital model-based engineering (IAWG, 2017). The challenges imply new or strengthened leadership capabilities, many that relate to a curation-type role, as well as re-examining basic leadership capabilities under the digital paradigm. New model curation leadership capabilities have potential to address many cited challenges related to

organizational and cultural hurdles, contractual and data management practices, security for single source of truth, and others.

Need for curation in model-centric engineering stems from the significant increase in models and model-related assets (libraries of data sources, techniques, etc.). Figure 19 illustrates the many decisions one would need to make in using models on a complex systems endeavor, such as an airport collaborative decision making system. This brings into question who owns such assets at an enterprise level, and how these are managed and used/reused over time.



**Figure 19 Many Decisions in Using Model-Centric Environments (Reymondet et al., 2016)**

Effective model curation necessitates clarity across the systems community in characterizing and handling models. It requires formalizing knowledge of models and determining a distinctive set of model characteristics (purpose, input/output types, logic, assumption types, model incompatibilities, etc.). Various types of models have been enumerated by the systems engineering community, but there appears to be insufficient attention given to model purpose itself. This is discussed in more detail in the IMCSE Phase 4 report (Rhodes & Ross, 2017). Reymondet et al. (2016) introduces the envisioned role of a curator, along with capabilities may be required in terms of understanding models.

## INVESTIGATING NEW LEADERSHIP CAPABILITIES

Under the premise that model-centric environments of the future will necessitate specialized leadership capabilities and competencies, a new leadership role for curation has been investigated. As the model-centric environments become increasingly complex and critically important, there is a need to more strategically lead and manage them. Empirical knowledge gathering has investigated the challenges and needs, and explored the potential roles and responsibilities for this curation role.



A model curation function (performed by a group of individuals) will have the objective of sustaining highest possible benefits and outcomes from the collective set of model assets and formal curation practices. Extending from the various types of curation roles and activities of other fields, the model curator's role is envisioned to include a number of major responsibilities and support of various staff. At the organization level, the curator may organize training and special projects related to model-based engineering. The model curator (curation function) would set and administer model-related policies and practices. The curator would ensure models and related documents are authenticated, preserved, classified and organized accordingly with model metadata standards. The curator may own the data management for models and related information, or oversee the ownership by other individuals or organization. As needed, a curator would meet with individuals and teams, who will create, use and re-use models, helping to determine a useful classification of both individual models and sets of models.

*The phrase “**active management and enhancement**” was chosen to distinguish curation from simply collecting and storing data and information.*

*Active management denotes planned, systematic, purposeful, and directed actions that make digital information fit for a purpose. It includes coordinated activities that allow users to understand and exploit digital information assets and to ensure their integrity over time.*

*Active management also refers to activities that ensure that digital information will remain discoverable, accessible, and useable for as long as potential users have a need or a right to use it. It may further involve securing digital information from unauthorized access.*

*Information management, data management, data stewardship, data governance, and digital archiving are related terms used to describe processes and activities that overlap with curation.... **What distinguishes curation from these other fields is its emphasis on enhancing the value of information assets for current and future use and its attention to the repurposing and reuse of information, both within and beyond the context in which it was first created or collected.***

Preparing the Workforce for Digital Curation, National Academies Press, 2015

**Figure 20 National Research Council Study on Digital Curation**

## **ENTERPRISE LEVEL MODEL CURATION**

IMCSE research suggests driving factors for model curation and a curation leadership role at the enterprise level. Although reuse of models can have benefits, the reality is that legacy models are not widely used beyond their original purpose. Rouse (2015) stresses that the wealth of existing models is often not used because of a lack of knowledge of these resources and the difficulty in accessing them. The lack of access to models, mistrust of models, and perception of legitimacy of models are all barriers in model reuse and longevity. Since model expertise is largely resident in individuals, the ability to select and compose sets of models is typically limited to the original use. In many enterprises, modeling competency is distributed across individuals and organizations, rather than leveraged at the enterprise level. Accordingly, the lack of a centralized leadership authority results in models being owned and managed only at a

local level. In some cases, modeling efforts are often duplicated across programs. Often, programs that lack model experts accordingly do not benefit from the collected wisdom of the enterprise. Potential benefits to other programs are not considered.

The digital paradigm shift is leading toward a situation where models are becoming increasingly valuable and ultimately have equal/greater value than the physical assets. Models exist at all levels of an enterprise (individual, program, business unit, enterprise) but not presently well-managed as enterprise collection. There is, however, the need to distinguish between the models that can be elevated to the enterprise collection (deemed of value and quality to be used across the enterprise, and worthy of distribution outside the enterprise (by exchange, loan, sale...), and the models that are used only at a local level and/or be designed to be used for quick studies, etc. Enterprise level models will need to have a “model pedigree”.

### **MODEL PEDIGREE**

Model pedigree was first described as “model demographics” by Gass & Joel (1980), and the term pedigree was subsequently used by Gass. A pedigree contains all of the information about a model, its origins and use over time. As described by Gass & Joel (1980), the purpose is to “enable the decision maker to determine the model’s status with respect to past achievements, theoretical and methodological state of the art, and the expert advice that went into its development”. While model documentation is typically developed, the content of the pedigree may contain information not always included in engineering model documentation materials. Given that IMCSE research on model-centric decision making has shown that trust is a key determinant in use of models, a pedigree provides information that engenders trust.

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### **ENVISIONING AN EXECUTIVE LEADERSHIP ROLE**

Many enterprises have established new leadership positions, such as a Chief Digital Officer (CDO). This role varies, but typically is a change agent for all things digital, with primary focus on creating business opportunities. There is frequent debate over the overlap with other executive roles and many feel this role may go away over time. Chief Data Officer (CDO) and Chief Analytics Officer (CAO) are other newer executive roles, given the rise of big data and data analytics. The roles, however, are not sufficient for the enterprises that depend upon model-centric engineering practice for designing, developing and operating engineered systems, as the emphasis is somewhat different.

As enterprises undergo transformation to become a model-centric enterprise, the model leadership role can be expected to evolve over time. Figure 21 shows a hypothetical description of the model leadership approach and enterprise characteristics relative to model-centric transformation.

<b>Paradigm Shift</b>	<b>Leadership Approach</b>	<b>Enterprise Characteristics Include...</b>
<b>Model Use Throughout Program</b>	“Local” model management	<ul style="list-style-type: none"> <li>• Models are primary artifacts replacing documentation</li> <li>• Limited reuse of models</li> <li>• Organization embraces importance of models</li> </ul>
<b>Model Reuse Across Programs</b>	Model leadership responsibilities	<ul style="list-style-type: none"> <li>• Models-based engineering as standard practice</li> <li>• Models are reused across programs in business unit</li> <li>• Model-centric enterprise culture</li> </ul>
<b>“Digital Twin” Lifecycle</b>	Enterprise-level leadership role	<ul style="list-style-type: none"> <li>• System “digital twin” maintained through lifecycle</li> <li>• Enterprise practices for model architecture (modularity, composability)</li> <li>• Model-centric culture embedded across enterprise</li> </ul>
<b>IP Inversion in Enterprises</b>	Model Curation Officer as top tier executive	<ul style="list-style-type: none"> <li>• Models (Digital Twins) are key deliverables</li> <li>• Model IP is more valuable than product, models are sold, exchanged, loaned</li> <li>• Innovations emerge from composability of models</li> </ul>

**Figure 21 Leadership Approach Evolves as Enterprise Transforms to Model-Centric Enterprise (hypothetical)**

#### **CHIEF MODEL CURATION OFFICER (POSTULATED NEW ROLE)**

The continued investigation of model curation in this phase has confirmed the need for evolving a leadership role for this purpose, which this report will refer to as Chief Model Curation Officer (CMCO) for purposes of discussion.

The CMCO is envisioned as an enterprise-level leadership role that focuses on the strategic management of the enterprise collection of model-based assets (Figure 22). A curator of institutional collections, such as museum curator, offers an analogy for the proposed responsibilities of the model curator. The museum curator’s role is an essential one where highly knowledgeable curators oversee collections of artwork and historic items, with support from archivists who appraise, edit, and maintain permanent records and historically valuable documents. Specialists and technicians are also involved in various capacities. The museum curator has deep knowledge of the collection, with responsibility for putting together purposeful special exhibits. The CMCO is envisioned to have a similar executive-level role overseeing the enterprise-level model collection, as well as having strategic responsibility for composing sets of models for special purpose. An example of special purpose is a model-based demonstration of new system capability in support of a competitive bid or market opportunity.

**Research in progress to develop and validate R&R, including:**

- Determine model accessions, de-accessions, acquisitions, loans
- Responsible for policies/practices and model pedigree standard
- Set guidance for use (e.g., model composition strategies)
- Set strategic goals for model-centric practice and environments
- Lead role for composing model demonstrators

*The museum curator has deep knowledge of the collection, with responsibility for putting together purposeful special exhibits. The CMCO is envisioned to have a similar executive-level role overseeing the enterprise-level model collection, as well as having strategic responsibility for composing sets of models for special purpose. An example of special purpose is a model-based demonstration of new system capability in support of a competitive bid or market opportunity.*

**Figure 22 Exploring the Curation Roles & Responsibilities (R & R)**

The role of the CMCO does not negate the need for model ownership and management at the local level. Not all models are suited for a collection-level asset, and many models will be the result of maturation of a local-level asset (e.g., developed on a particular program or in a research project). The CMCO is envisioned as the gatekeeper for selection of models elevated to the enterprise-level model collection (model accessioning), as described in Figure 23.

### **Model Accessioning**

- Accessioning is the process of officially accepting models (and sets of models) into the enterprise level model collection.
  - An accession is the acquisition of a single model or set of models, from one source, under one type of transaction (elevated to global, exchange, purpose...), as of a single date
- Accessioning establishes legal ownership, IP, validity of pedigree, etc.
  - Developed or acquired? Or existing local asset elevated to global asset? Adapted from open source? Purchase or exchange?
- Condition at accession recorded, establishing initial pedigree
  - Model and pedigree info recorded with unique identifier
  - Placed under CM

**Figure 23 Example Role: Model Accessioning**

### **POTENTIAL FORMS**

During this phase of research, continued knowledge gathering and semi-structured interviews with executives were conducted to formulate a preliminary set of potential forms for a model curation function. Figure 24 describes seven alternate forms for an enterprise to execute the role and responsibilities of an enterprise model curator function. These forms are: centralized – top tier, centralized – dotted line, franchised, collaborative, dual hat, delegated, and outsourced. Further research is needed to investigate, validate and refine this initial taxonomy. Over time, studies are needed to understand how effective these forms are for various enterprises, and under which conditions one might chose the form.

Form	Implementation	Under what conditions
<b>Centralized – Top Tier</b>	CMCO is a top tier executive reporting directly to CEO	High performing model-centric engineering enterprise or has a very aggressive goal to become one. Culture has fully embraced model-centric engineering across the entire enterprise, and believes model leadership is key to competitive advantage and to innovation
<b>Centralized – Dotted Line</b>	CMCO has enterprise level authority, “dotted line” reporting to CEO	The enterprise is rapidly becoming a high performing model-centric engineering enterprise. The CMCO needs enterprise level authority to make and implement strategic decisions, but is not ready to make the CMCO a full member of the executive management team.
<b>Franchised</b>	Enterprise segments have CMCOs, conforming to enterprise defined policy and role.	For very large enterprises with varied cultures within enterprise segments, it can be difficult to have one top-tier CMCO. A franchised form enables the enterprise to establish the role and responsibilities at enterprise level. CMCOs are appointed in each enterprise segment reporting to its top executive, conforming to enterprise defined policy and role.
<b>Collaborative</b>	Virtual CMCO role through collaborative committee	The enterprise does not wish to appoint a single individual to the CMCO role at this time, but recognizes the need to have model curation capabilities. An appointed collaborative committee provides a “virtual CMCO” by serving as a strategy-setting and implementation oversight body. An instance where this might be a preferred form is an enterprise that is comprised of many newer acquisitions that have strong heritage culture and processes.
<b>Dual Hat</b>	CMCO is one of two roles played by an executive	An enterprise that is working toward becoming a model-centric enterprise but still uses legacy approaches is likely not ready to make the investment needed to appoint an enterprise CMCO. A dual hat form, while challenging to perform, enables the enterprise to allocate specific model curation responsibilities to an existing leader (e.g., CIO, CTO, CDO).
<b>Delegated</b>	CMCO responsibilities are delegated to a committee, to one or more individuals	Similar to “dual hat” but the role is not specifically delegated; the responsibilities are delegated as add-ons to an existing role, or to the responsibilities of a standing committee. This implementation form is weaker than the dual hat, but does acknowledge these responsibilities as specific to MC, as a precursor to a formal role.
<b>Outsourced</b>	CMCO role is performed by an external hire	Temporary hiring of an outside CMCO may be the only option available to an enterprise that recognizes the need for the MC role but does not have expertise or capacity to staff it from within. It might also be a form used by an enterprise that is not convinced of the value of having an CMCO, but wants to have trial implementation.

**Figure 24 Organizational Forms for Chief Model Curation Officer**

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## MODEL CURATION LEXICON

Table 1 enumerates a lexicon, which is evolving through discussions with research stakeholders and investigation of other fields.

**Table 1 Model Curation Lexicon (continues to evolve)**

<b>Chief Model Curation Officer</b>	A designated professional, authoritative role – at the executive level of the enterprise - entrusted with the ownership, tracking and use of model-based assets.
<b>Model Accessioning</b>	The formal process of accepting and recording a model as a collection object in the enterprise level model portfolio. Accessioning addresses the legal, IP and ethical issues in model acquisition and development.
<b>Model Acquisition</b>	The act of acquiring a model through an arrangement with the model owner (e.g., through purchase, trade, or other business transaction).
<b>Model Cataloging</b>	The formal process of making a model available for use through recording it in a catalog or directory, and tracking it throughout the model lifecycle.
<b>Model Collection</b>	The collection of model-based assets that is possessed by an enterprise, including those developed by the enterprise, acquired by the enterprise, and temporarily resident in the collection (e.g., leased, on loan).
<b>Model Collection Object</b>	A model or model-related object that is a unique asset in the enterprise's collection. An object is assigned a unique identifier.
<b>Model Curator</b>	A designated professional role entrusted with the ownership, tracking and use of model collection objects, and possessing designated authorities for managing and controlling models.
<b>Model Composition</b>	The process of composing models and model-related information that provides collective value beyond the individual models.
<b>Model Composability</b>	The characteristic of an interrelated set of models that enables them to be combined in accordance with given modeling formalisms.
<b>Model De-accessioning</b>	The formal process of removing a model as a collection object from the enterprise level model portfolio.
<b>Model Demonstrator</b>	A composed set of models with interactive interfaces for the purpose of demonstrating context-specific capability. Demonstrators enable the modeled system to be experienced by an individual through conveying cogent information and where possible, the use of interactive interfaces.
<b>Model Loan</b>	The act of temporarily acquiring a model through an agreement whereby the model owner agrees to share the model with the model acquirer for a specified time and specified terms (e.g., terms of use, remuneration, etc.).
<b>Model Metadata</b>	Descriptive metadata is contextual data about the model object(s). Metadata documents characteristics and used for indexing, discovering, identification. Provides user discovery of, access to, and management of an object.
<b>Model Pedigree</b>	Model-associated information that describes model origin, development process, originators and developers, assumptions, expert knowledge, model enhancements, investment costs, versions, change history, etc.



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## **DISCUSSION AND FUTURE RESEARCH**

The research has identified sociotechnical leadership capabilities that provide the ability to execute digital model-based engineering at the program and enterprise levels. The next phase of research seeks to mature a framework for assessing model-centric enterprise capabilities. This framework will be developed using an evidence-based approach, which integrates empirical research evidence, decision maker/practitioner's expertise, and situational perspectives (values, needs, stakeholder preferences such as risk tolerance). The assessment framework will accommodate assessing capability respective to the state of transformation from traditional to fully digital model-based engineering. Model-centric enterprise capabilities identified in prior phase research include model composability, transparency, accession practices, model valuation practices, model trust and others. Ultimately, having a common framework for model-centric enterprise capabilities enables better understanding of effective practices, accessing transformation progress and generation of evidence through systematic study, providing benefits across the systems community.

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## **SUMMARY**

Under the premise that model-centric environments of the future will necessitate specialized leadership and competencies, a new leadership role for curation was further investigated. In this phase, alternative stages were identified for organizations transforming under the digital paradigm. Specific needs were identified for establishing leadership and practices for model curation. Investigation resulted in seven different types of organizations for implementing model curation, based on different needs and organization forms. Research findings were shared with research stakeholders as a preliminary validation of needs and emerging practices. The need for an instrument for organizations to assess their model leadership capabilities and risks was confirmed in a technical exchange workshop and other meetings with research stakeholders.

## CONCLUSION

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IMCSE research seeks to inform and contribute new knowledge, processes, methods and tools to improve the interactivity of humans and models in support of systems decision making. The research is grounded in two assumptions. The first is that systems success depends upon effective “human-model teaming” and the second is that specialized leadership and competencies will be required to realize the vision of model-centric engineering.

Phase 5 research included three areas of focus, which built upon the prior phase research. These are:

**Human-Model Interaction.** The empirical study on model-centric decision making was completed with 30 experts, resulting in findings and preliminary guiding heuristics. Outcomes of the investigation of human-model interaction were integrated and shared in state of the practice papers and presentations. Heuristics were further refined and validated, with four proposed application areas. A technical exchange workshop was held to gather practitioner feedback on study results and directions for transitioning heuristics to practice.

**Interactive Epoch-Era Analysis (IEEA).** The IEEA framework and prototypes were applied in a commercial ship design case to test applicability to a non-defense application and analysis of changeability options. The designed experiment on impacts of decoupled visualization and interaction was completed. The framework, prototypes, case-based impact studies, and experiment results were completed.

**Curation of Model-Centric Environments (Enterprises).** Model curation was further explored through literature and interaction with research stakeholders. Investigation areas included alternative forms for curation leadership, curation practices, and data/model pedigree. Preliminary exploration of a concept for an assessment instrument for curation capabilities was conducted. A technical exchange session was held to gather feedback on interim research, identify potential transition opportunities, and elicit information on state of practice and needs for the future.

IMCSE research has been presented and discussed with practitioners and sponsors in numerous research meetings and workshops, as well as with other researchers in the systems community. These activities have raised the awareness of challenges and needs surrounding human-model interactivity, and there is a growing community of interest within the SERC and the larger systems community.

IMCSE research will continue in Phase 6, with two areas of focus. The first is guiding principles and patterns for human-model interaction. The second area is a framework for assessing model-centric enterprise capabilities.



## APPENDIX A: LIST OF PUBLICATIONS RESULTED

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Bone, M.A., Blackburn, M.R, Rhodes, D.H., Cohen, D.N. & Guerrero, J. A. (2018, January). Transforming Systems Engineering Through Digital Engineering. *Journal of Defense and Modeling Simulation (JDMS)*.

Curry, M, Rehn, C.F., Ross, A.M., & Rhodes, D.H. (2017, March). Designing for System Value Sustainment using Interactive Epoch-Era Analysis: A Case Study from Commercial Offshore Ships. *15th Conference on Systems Engineering Research*. Los Angeles, CA.

Curry, M. (2017, June). Design as Search Problem: Interactive Visualization for System Design under Uncertainty. Doctoral Dissertation. Massachusetts Institute of Technology.

German, E.S. (2017, June) *An Investigation of Human-Model Interaction for Model-Centric Decision-Making*. TPP SM Thesis, Massachusetts Institute of Technology.

German, E.S. & Rhodes, D.H. (2017, March). Model-Centric Decision-Making: Exploring Decision-Maker Trust and Perception of Models. *15th Conference on Systems Engineering Research*. Los Angeles, CA.

Reid, J.B. & Rhodes, D.H. (2017, March). Classifying Emergent Behavior to Reveal Design Patterns. *15th Conference on Systems Engineering Research*. Los Angeles, CA.

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## APPENDIX B: CITED AND RELATED REFERENCES

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